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SEISMIC RESPONSE OF DEEP SEDIMENTS IN MID-CONTINENT (USING BROAD BAND AND SHORT PERIOD SIGNALS)

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Abstract:

We assess seismic site resonance periods in Memphis, Tennessee, associated with shallow low-velocity loess deposits using Horizontal to Vertical spectral ratios of ambient seismic ground motions. Many sites within the Mississippi embayment consistently feature spectral H/V ratio peaks at three distinct frequencies. The two longer period peaks (3-4 s, and ~1 s) are associated with resonance within deep (~800-1000 m) unconsolidated sediments that overly hard Paleozoic rocks. The highest frequency peak (2-10 hz) reflects shallower interfaces. Within Memphis, the period of this peak correlates with the thickness of the surface loess deposits. Using loess thicknesses observed in shallow boreholes as calibrations, we estimate the average velocity of the loess deposits at 250 ± 10 m/s. This estimate assumes that the peak is produced as the constructive interference of vertically traveling shear waves. Careful analysis of observations at four sites reveals that this assumption may not accurately represent the process that produces the peaks but rather provides a rough estimate.

Introduction

Background and Motivation

In this paper we test the ability of recordings of ambient ground motion (seismic noise) to constrain the near-surface geological structure in the metropolitan Memphis area, Tennessee (MMA). The source of ground motions used in our study is not known, but is thought to be local cultural and natural sources (traffic, trees, etc). The observations (periods of peaks in spectral ratios of horizontal-to-vertical ambient ground motions) do not uniquely define a velocity structure, but rather must be calibrated with observations from other methods. Once calibrated, they may be used to constrain the depth and the velocity of the shallowest layer.

We were motivated to undertake this work to explain observations acquired during earlier studies in which we analyzed horizontal-to-vertical power spectral ratios (HVPSR) of ambient ground motion. In our earlier studies (Bodin & Horton 1999, Bodin *et al.,* 2001) we observed a strong site resonance throughout the Mississippi embayment (Figure 1) in HVPSR due to energy trapped in unconsolidated sediments of Cretaceous to Holocene age that lie unconformably on well indurated Paleozoic limestone. Power spectral ratio peaks with amplitudes of about 100 were found at rather long periods (4.6 seconds in the MMA). (We ascribe little significance to the amplitude of the HVPSR peaks both for theoretical reasons discussed below and because the peak amplitudes depend on how the analyses are performed, but such large peaks assure their robust detection). Figure 2 reveals the structure of a "typical" HVPSR in the MMA. The 4.6 s period peak, T_o, is clearly the largest peak. The peak labeled T_1 was nearly always observed at a period of very near to 1/3 that of T_o, and interpreted as a first higher harmonic of T_o. Bodin et al., (2001) noted the presence of a peak at even shorter period, which they labeled T_L but did not study.

This paper focuses on the peak labeled T_L, which appears small compared to T_o and T_1. However, as we shall show below, T_L: (1) correlates in frequency to shallow geological structure, and (2) is consistently observable at a site. Unlike T_1, which could easily be explained as a first higher multiple of T_o (Bodin *et al,* 2001), we do not believe T_L to represent a higher order multiple of energy trapped within the entire thickness of unconsolidated sediment. Rather, we hypothesize that it is a geophysical marker for an interface at the base of a shallow low-velocity layer.

Despite an abundance of recent studies of ambient ground motion HVSPRs, no uniform method of interpreting the data and unraveling the implications for the shallow structure has emerged. This arises undoubtedly because the sources (and therefore the propagation mode) of the seismic energy used in the analyses are usually unknown and vary from study to study (and even site to site), combined with the wide variety of sites conditions in which the methods have been applied. The presence of numerous robust peaks complicates any interpretation, however the presence of several HVSPR peaks at sites in the Mississippi embayment is probably related to the complex deep unconsolidated soils there. But in the absence of data from arrays of seismometers we cannot distinguish the mode of propagation of seismic energy. A full review of analytical techniques of HVSPR and the circumstances in which they may be applicable is beyond the scope of this paper. However, the likely interface to be associated with peak T_L (as we will demonstrate below) is a fairly weak velocity Vs contrast (1.5 to 2) at the base of superficial silt deposits. Numerous authors (e.g., Kudo, 1995, Bard 1998, Stephenson 2003, Malischewsky & Scherbaum, 2004, and Bonnefoy-Claudet, 2004) have studied the effects of propagation as Rayleigh waves on the HV ratios. Taken together, these studies demonstrate that caution should be used in quantitative interpretation of HVSPR in such situations. In this study we first infer from the spatial distribution of our observations the association between a robustly observed peak and a particular interface. Then we attempt to quantify the relationship between the frequency of the peak and the thickness and velocity of the shallowest layer. As a marker, we employ the most widely applied estimate, generally applicable at sites with a large seismic impedance contrast (low speed overlying high speed), and vertically propagating S waves are resonating within the low speed layer. This condition would be expected to lead to a peak in the H/V spectral ratios at a period (T_r) of:

$$T_r = 4Vs/H \tag{1}$$

where Vs is the average shear wave speed of the low speed surface layer above the impedance contrast at a depth H (*e.g.,* Murphy et al., 1971). If the spectral ratio peak in question is due to another propagation mode (*i.e.,* Rayleigh wave ellipticity, or the dominance of Love waves, either in the fundamental or or higher modes) considerable uncertainty (~±50%) may be introduced into the interpretation (REFS). We shall discuss the implications of this for the current study later in this paper.

Our ultimate reason for employing ambient seismic ground motions is to study shallow structure to help constrain shallow seismic wave propagation effects (site effects) for seismic hazard studies. In the MMA, relatively low earthquake occurrence rates and sparse seismic station coverage combine to make observational constraints of earthquake sources on site effects rare. Moreover, even though the sources of seismic microtremor are not well characterized, ambient ground motions at a site may provide different constraints than do other shallow geophysical techniques in that the observation is based on a physical phenomenon of direct engineering importance: the variation of the spectrum of seismic ground motions between sites.

We first briefly describe the geologic setting and geotechnical soil properties of the study area. After this we present the methods we used. Then we show the results of a line of samples across Memphis that reveals the spatial coherence of a signal best associated with a very shallow interface. We explore in greater detail a few sites where studies of the shallow geological and geotechnical properties have been carried out previously to see what might have led to our results. Finally, we discuss the significance of our observations for seismic hazard assessment and as a geophysical technique.

Observations

Surface Geology and Geotechnical *Resumé* of the Study Area

The study area lies near the axis of the Mississippi embayment, a broad syncline that plunges gently to the southwest, forming a re-entrant of coastal plain type sediments into the continental interior (Figure 1, Stearns, 1957). For our purposes, the embayment may be thought of as a trough of well-indurated Paleozoic carbonates and shale onto which has been deposited largely unconsolidated clastic sediments of late Cretaceous and Cenozoic age. The poorly consolidated sediments beneath Memphis are 900 m thick. The surface geology of the MMA consists of Eocene and younger sediments as shown in Figure 1 (Miller *et al.,* 1966).

This study focuses on observations related to the shallower (~30 m) sediments within the MMA, which includes Eocene sands (the Memphis Sand) and younger sediments. Table 1 contains a summary of geology and lithology of the shallow sedimentary units. Standard Penetration Tests (SPT) within the Eocene Memphis Sand typically yield N-values (blows per foot) of 50 to >100 expected for more consolidated "rock-like" materials. In the MMA it is generally 150 to 270 m thick. The upper boundary is defined by a sand-clay contact (Criner *et al.,* 1964). Where this contact is not distinct, it is gradational and the boundary is placed arbitrarily at the midpoint of this gradational sequence (Criner *et al.,* 1964). The Memphis Sand dips gently to the west and outcrops throughout west Tennessee along a north-northeast trend (Figure 1).

Stratigraphically above the Memphis Sand lie three formations of upper Eocene age (Table 1). These three formations are similar in composition and as a result are very difficult to distinguish throughout this study area without detailed examinations (Kingsbury & Parks, 1993). Because most of the borehole data that was available for this study does not distinguish between the three formations, we will refer to these formations as the "upper Eocene clays." The SPT N-values vary from 15 up to 60 and, for very stiff sand sections, up to 80. This wide range is due to the heterogeneous nature of this section. Materials can range from loose sands, dense sands, or very dense clays. These upper Eocene clays range in thickness from 0 to 110 m. They outcrop along the bluffs of western Tennessee and along stream cut-banks in eastern Shelby County and Fayette County. Aside from bank exposures, outcrops are limited due to an overlying blanket of Plio-Pleistocene and Holocene deposits. The upper boundary is placed at the contact between the clay of the upper Eocene and the overlying sand and gravels of the Plio-Pleistocene fluvial deposits, silt to clayey silt of the Pleistocene loess, or sand, silts, and clays of the Holocene alluvium (Criner *et al.,* 1964). This upper boundary, an erosion surface, marks an unconformity and is a sharp contact.

In upland areas, Pliocene (?) to Pleistocene fluvial (terrace) deposits (Table 1) overlie the upper Eocene clays. Cementation in the fluvial deposits ranges from complete (rare) through partial (common) to entirely absent (common). Cementation is more common in the lower sections of the deposits (Criner *et al.,* 1964; Carmicheal *et al.,* 1997). SPT N-values range from 12 to >100, the range probably reflecting the degree of cementation. Thickness varies up to 30 m. They are present from the bluffs eastward throughout Shelby County. Exposures are along the bluffs, in streambeds, along cut banks, and in quarries. The upper boundary is placed at the contact between gravelly sands and the silt or silty clay of the overlying Pleistocene loess deposits (Potter, 1955).

Pleistocene eolian loess deposits overlie the fluvial deposits and form most of the MMA surface (Table 1). The loess consists predominately of silt, clayey silt, and silty clay (Rodbell, *et al.,* 1997). Loess in the MMA may consist of up to four layers (McCraw & Autin, 1989; Parks, 1993; Rodbell *et al.,* 1997) representing different periods of deposition (Parks, 1993, McCraw & Autin, 1989). The loess is thickest (up to 20 m) at the bluffs and thins to the east, eventually pinching out near Somerville, TN (Figure 1). It is unclear how each of the four loess layers vary in thickness throughout the study area. Loess is also generally thicker at topographically high areas and thinner in valley areas (Rodbell *et al.,* 1997). Soil boring logs we examined did not permit us to differentiate between the four loess layers. A “transition zone” is observed between the loess and the fluvial deposits from clayey silt or sandy silt at the top to silty sand at the base (Carmichael *et al.,* 1997; Hasan & Peyton, 1998). Soil borings indicate a correlation between the change in texture of this transitional zone and an increase in SPT N-values. SPT N-values typically range from 4 near the surface and increase to 25 in the transitional zone, indicating a transition from loose material to material with a moderate strength expected for loess.

The other major surface unit of the MMA is the Holocene and Pleistocene alluvium (Figure 1, Table 1). Alluvium covers the Mississippi River floodplain as well as the other tributary alluvial plains of western Tennessee. Alluvium generally consists of an upper layer of silt, clay, and sand and a lower part of sand and gravel (Fisk, 1944; Saucier, 1994). Alluvium thickness ranges from 0 to 53 m and is thickest beneath the Mississippi River alluvial plain. SPT N-values generally do not exceed 20 for upper parts of the alluvium and can increase to more than 40 near the base of the Mississippi River alluvium. In general it is considered to be a very loose material.

Methods

In this study we recorded ambient ground motions on a Guralp Systems Inc. (GSI) model CMG-40TD seismometer, which has a flat response to ground velocities from 0.03 to 50 Hz. At free-field sites, the seismometer was placed in a plastic bag for protection and then lowered into a 50 cm deep hole excavated for the purpose, oriented to cardinal directions, leveled, and then buried using the displaced soil. After the seismometer stabilized for 8 to 10 minutes, ground motion was recorded for either 15 minutes or 12 to 24 hours (if continuously recording overnight). It was our experience that burying the seismometer enhanced the ground motion signal relative to thermal, electronic, and wind-induced casing vibration noise, particularly at longer periods. If it was not possible to bury the instrument, it was placed on the concrete ground floor of a small building. The data were sampled at 100 sps and were recorded on a laptop PC running GSI's data acquisition software.

In the office, the time series and their spectra were scrutinized for problems (e.g., start-up transients, clipping, internal instrumental noise, thermal fluctuations etc.) and those segments with problems were not used to compute spectral ratios. The time series were then used to compute the HVPSRs. Computations for the power spectrum of each component were performed using the Welch periodogram method with MATLAB. Means were removed and then tapered using Hanning tapers in windows of either 4096, 2048, 1024, 512, 256, or 128 points long. The windows were overlapped by half of the window length. Power spectral ratios [$T_{H/V}(\omega)$] for the average of the two horizontal spectra [$H_{NS}(\omega)$ and $H_{EW}(\omega)$] to the vertical power spectra [$Z_V(\omega)$] were then calculated (Seht & Wohlenberg, 1999):

$$T_{H/V}(\omega) = \frac{\left[H_{NS}(\omega) + H_{EW}(\omega)\right]\big/2}{Z_V(\omega)} \tag{2}$$

Peak Identification and Assignment of Uncertainty

Identifying robust peaks in the HVPSRs at frequencies above 1 Hz was challenging, and particularly so at urban sites with multiple ground motion sources and with shorter recording times. We will discuss the significance of this point in more detail in a later section, but here we seek only to describe what we needed to do in order to be sure of a peak's identity and in order to ascribe uncertainties to its frequency. In brief we believe that numerous nearby, and usually transient, sources of ground motion at noisy sites could make transient HVPSR peaks appear in our analyzed data. Peaks that reflected the velocity structure at a site would be stationary in time. Therefore, our time series were generally broken up into sub-sections, and each sub-section analyzed separately, and only peaks common to all sub-sections were measured. At a few sites where we had particularly long recording times, and at which we returned several times during a 6-month study duration, we were able to assess the temporal stability of the ~5 Hz T_L peak.

These peaks were generally found to be robust (Smith, 2000). Data processing also influences the shapes and amplitudes of peaks in a spectral ratio. The breadth and smoothness of a peak in the frequency domain is in part controlled by the length of the window used in the FFT. Choice of the number of time series points to use to make a interpretably smooth (but not overly so) spectral ratio was initially a subjective decision. For the 2 hz-10 Hz band sampled at 100 Hz, we found that 256-sample windows (~2.5s) worked the best. Longer windows tended to "break up" robust (temporally stable) peaks into families of peaks each of which was not temporally stable. Since we can't interpret them at this point, we assert they are not important to our purpose. Appropriately smoothed, the resultant peak is a stable and robust feature that we feel is the "best estimate" of a site's resonance frequency in the 2-10 Hz pass band.

Picking the peak was done manually, and in this study we report the frequency of the highest value of the robust peaks in the 2-10 Hz pass band as described above. We also report an uncertainty for peaks that reflects the peak width at half of its height above the surrounding data level. Figure 3 is a typical example of a robust ~5 Hz peak we labeled T_L, and further illustrates how we assigned uncertainty to the peak. This method of assigning uncertainty incorporates the understanding that there has been spectral smoothing, geometric shape issues, etc. While not a statistically defined uncertainty, we would not expect to find resonance values outside of this range of when the measurement was made, the window length used during data processing or by the operator performing the picking.

Results

In this section we first examine the correlation of T_L with shallow geological structure, particularly the recordings from sites with different thicknesses of loess. Then we examine four sites in greater detail to try to better understand the physical process underlying the observed correlations. Figure 1c shows the sampling localities for the observations presented, and their relationship to the surface geology.

T_L and Loess Thickness

The loess that caps the Memphis stratigraphy is generally thickest along the Mississippi river bluffs east of the river, and thins progressively with distance east. Therefore, we hypothesize that a line of sites running across the MMA from west to east would reveal gradually decreasing T_L periods if produced by site resonance via a model represented by equation (1). Figure 4 reveals that this is hypothesis is supported by the observations from our transect. A separation into three spatial parts of the periods and characters of short period peaks reflects differences in the shallow geological structure.

Segment A lies west of the bluffs, on the Mississippi alluvial floodplain where the upper 30 to 45 m consist of alluvium (Fisk, 1944). The short period peaks cluster, with one exception, at 0.2 s. Also, the peaks are rather wide, as reflected by the large uncertainties. The suggestion of a trend toward higher frequencies toward the east in this segment mirrors the thickness of the alluvium. In this region of the embayment, the alluvium is thinner (shorter periods) near the river and becomes thicker (longer periods) away from river (Fisk, 1944). Good borehole control is lacking in this segment, so it is difficult to be more detailed.

Within segment B, which encompasses sites with loess mapped at the surface, there is a systematic decrease in the period from 0.2 s to 0.07 s. The peak here is more sharply defined than it is in segment A. As shown in Figure 4, the pattern of decreasing period eastward is in close correspondence with the pattern of thickness of loess as reported in boreholes nearby to the recording sites.

Within segment C, values of T_L for three of the four sites cluster at about 0.3 s. Sparse borehole data in this segment make it difficult to be concrete about possible structures associated with a .3 s peak. A geotechnical study from the western edge of segment C (Brahana *et al.,* 1986) describes the upper 61 m as predominantly sand (of the Claiborne Group), although at a depth of 15.2 m the SPT N-values (correlated with rigidity, and hence probably shear-wave speed) increase. Therefore we speculate that the cluster of peaks at 0.3 s is also probably not related to a lithologic interface, but rather to a change in rigidity of the sand. If so the corresponding average shear-wave speed for ~15 m of sand (from equation 1) would be 203 m/s. This does not seem unreasonable for low-rigidity sands. The fourth site in segment C, has a peak at 0.053 s, but an electronic noise spike in the data at ~ 0.24 s obscures the identification of any spectral ratio peaks in this passband. Lack of borehole data near this site make it difficult to identify any structure associated with the 0.053 s period peak.

Shear Wave Speed of Loess

So far we have demonstrated that the short period peak might reflect the shallow geology at a site. We now proceed to test the utility of our observations for constraining a parameter of geotechnical and geophysical interest, the average shear wave speed of surface deposits. It order to do this, we will first restrict our analysis to sites of high quality data (*e.g.,* very clean time series and spectra) and for which detailed borehole data were available within 1 km of the site (Figure 1C). We then fit the observations of resonance period T_L and thickness of loess, H, to Equation 1, and solve for the best average uniform shear wave speed, Vs. If the fit to Equation 1 is forced through the origin, the method provides a self-consistent estimate of average uniform shear wave speed for the surface layer (loess). The results, illustrated in figure 5, yield an estimate of 250 ±10 m/s. The correlation coefficient (R^2) is 0.74 indicating a reasonably good fit.

Comparing our estimate of Vs for the Memphis Loess with other measured values (Toro *et al.,* 1992; Hwang *et al.,* 1990; Huo & Hwang, 1995; Liu *et al.,* 1997; Hasan & Peyton, 1998; Hall, Blake, and Associates, Inc., personal communication; and Rob Williams, personal communication), 250 m/s appears to be reasonable, although on the high side as an estimate for the average loess velocity. Gomberg *et. al,* (2003) have compiled a number of published borehole-derived Vs and formation thickness estimates from throughout Shelby County into a structural map. They determine an average Vs of 192±37 m/s for the loess, and an average of 268±72 m/s for the underlying fluvial deposits. The ranges of the distributions that Gomberg *et al.* , (2003) determine suggest that the resonance peak we observe may in fact be associated with the strong velocity contrast within the fluvial deposits, where indurated gravels are known to occur (*e.g.,* Potter, 1955). Alternatively, if the T_L peaks are uniformly produced by Rayleigh wave ellipticity, then the interpretation based on equation (1) can be expected to overestimate velocities by as much as 30%. Our results compare favorably with shallow active source seismic experiments. Williams *et al.,* (2003), for example, estimated that shallow velocities (VS30, average velocity in the shallowest 30 m) averaged 262±45 m/s among all sites studied in Memphis east of the Mississippi, i.e., on loess sites.

Case Studies

We are not aware of reports of other locales in which several different periods of site resonance, which may correlate with velocity contrasts at several depths, have been observed in ambient ground motions. We would like to understand how the good statistical correlation between loess thickness and period of T_L arises. In order to study this, we selected several sites at which more detailed lithologic and/or geophysical information was available to look at in greater detail. Those results are presented below.

Overton Park This site is within an urban park. We recorded ground motions here overnight to avoid the heavy daytime cultural noise. Spectral ratios reveal two peaks in the 0.1 s to .5 s period range, at 0.16 s and 0.24 s (Figure 6a). Geophysical and lithologic information for the Overton Park site in midtown Memphis (Smith, 2000, Ng *et al.,* 1989) suggest a shear-wave velocity of 275 m/s for a thickness of 12 m of loess that overlie fluvial deposits (Vs = 440 m/s). Underlying the fluvial deposits, the upper Eocene clay comprises a low-velocity zone (Vs = 275 m/s). Below 22 m deep (to at least 30 m) the upper Eocene clay is faster (Vs = 555 m/s). Given this velocity structure the two impedance mismatches (at 12 m and 22 m depth) would seem to have the potential to produce SH-wave site resonance via Equation 1 at two nearby periods. Using the one-way S-wave travel time divided by the aggregate thickness to compute average velocities for the upper 12 m and the upper 22 m predicts resonances at 0.19 s and 0.30 s respectively. The periods of the two observed HVPSR peaks are near to, but shorter-period than, the expected values (the observations would suggest a Vs ~15% higher than observed in other studies). These results suggest that the short period peak (0.16 s) is related to the impedance contrast of the loess-fluvial deposit interface. The second peak appears to be related to the impedance contrast within the upper Eocene clays.

Shelby Forest Shelby Forest is an area remote from cultural noise (Figure 1). Perhaps because the cultural noise is so low here, the T_L signal in the spectral ratios appeared very clearly. Spectral ratios were calculated from 15 minutes to the 60 minutes of recorded ground motion. Figure 6b shows a typical spectral ratio from Shelby Forest, revealing a large peak at 0.19 s. The soil profile consists of 12 m of loess underlain by ~8 m of fluvial deposits. Below this, from a depth of ~20 m to the base of the boring, sediments consist of upper Eocene marine clays and sands. Shear-wave speeds obtained from down hole testing (Liu *et al.,* 1997) range from 196 m/s to 253 m/s for the loess, and from 327 m/s to 427 m/s for the fluvial deposits. The upper Eocene clays beneath this are 287 m/s near their top and gradually increase to 495 m/s at the base of the profile. Using the maximum and minimum speeds reported by Liu *et al.,* (1997) for the loess leads to an expected range for the site S-wave resonance period to be between 0.19 s to 0.25 s, in agreement with the observations.

St. Jude Hospital (SJH) SJH is located in the heart of downtown Memphis. The site is very near to a busy interstate freeway, and is extremely noisy. An overnight measurement was made within 100m of the source of geophysical and lithologic data. The results, illustrated in Figure 6c, are puzzling. A robust (temporally stable) peak is observed that encompasses the period at which a resonance peak might be expected. However, the peak is undistinguished and, given its amplitude of less than unity, might arguably not be a peak at all. Other studies suggest that at the site a low speed surface layer (Vs = 260 m/s) 17 m thick overlies a high-speed layer (Vs = 530 m/s). These shear wave speed layer boundaries do not correlate in depth with the lithologic layers (Rob Williams, personal communication) at this site. The surface low velocity layer includes the loess and upper portion of the fluvial deposits and coincides with the depth SPT data indicate an increase in rigidity (increase in N-values). The high velocity layer includes the basal section of the fluvial deposits and upper portion of the upper Claiborne sands and clays. A resonance period of 0.26 s may be expected at SJH based on the geophysically-determined velocity model.

TVAC Site TVAC is located in suburban MMA in another neighborhood of such high cultural noise that our HVPSR techniques were challenged. The roadway adjacent to the site carried a high volume of traffic throughout the day and night. Also, at this site is a major power substation with a large number of high-tension power lines in the area. Observations here lasted 14 hours and were made at a location approximately 400 m from where other geophysical and geotechnical observations were gathered. Figure 6d shows a spectral ratio from this measurement revealing a peak at 0.15 s. An HVPSR peak with a value of 0.36 s was intermittently present and was more readily apparent during recordings in which traffic noise is present, however it does not meet our criterion of robust, and was identified only after we began looking for it. Nor were there any other robust peaks in the period range of interest. The SPT data and lithologic description are composites based upon several borehole data. Shear-wave velocities were determined from down hole and cross-hole testing. The shear-wave velocity profile of this site differs considerably from the sites previously described. Shear wave speeds of the loess reach 379 m/s, much higher than seen at the other sites. Moreover, TVAC's fluvial and upper Eocene sections are low velocity zones relative to the loess and Memphis Sand. Velocity variations are seen within the fluvial and upper Eocene units. The most significant difference between this site and the others is that the loess is a high velocity layer overlying the lower velocity fluvial deposits. Given this velocity structure, we would not expect to see a resonance related to the loess-fluvial deposit interface. Instead, we expect that either or both of the impedance contrasts at depths of 25.6 m and 36.1 m might be sufficient to produce S-wave resonances. Periods of 0.34 s and 0.47 s are estimated for the shallow and deep impedance contrasts, respectively.

The .15 s period peak observed at TVAC, given the velocity structure stated in the last paragraph, would correlate to a depth within the fluvial deposits. Alternatively, the loess properties and those of the underlying fluvial deposits in this area might vary significantly laterally and we cannot rule out the presence of an energy-trapping indurated layer at our recording site not encountered by other studies. However we have no evidence to support this possibility. Although there is apparently a large impedance contrast at the upper Eocene/Memphis Sand interface, evidence of it in the spectral ratios is absent.

The individual site analyses suggest that identifying structural boundaries at an individual site with the methods we have employed is chancy. At two, and arguably three, of four sites, our results compare favorably with the results of other geophysical and geotechnical studies for characterizing depth and/or thickness of shallow units forming a high impedance contrast (slower over faster). For two sites (SJH, TVAC) with very high ambient noise levels, expected peaks were either not apparent, or difficult to distinguish. And at TVAC, our method observed an apparently incorrect short period (albeit weak) signal. There appears to be "good noise" and "bad noise" as far as ambient motions exciting an observable site resonance from shallow features within the Mississippi Embayment. And also perhaps there are "good sites" (where conditions produce observably strong resonance given the input ambient motions) and "bad sites" (at which resonance effects are weak or absent).

We provide the following heuristic hypothesis for why high ambient noise levels might obscure site resonance effects in HVPSRs. Cultural noise sources might be expected to produce largely vertical ground motions near the source. For example, traffic (a common urban noise source at high frequencies) might be thought of as an ensemble of moving vertical point forces. If peaks in the HVPSRs represent trapped SH wave motion at those frequencies, then the source of the SH motion might not be simply related to the nearby vertical noise source. In other words, near the source of surface-produced vertical-component motion the vertical spectrum may be so high that the amplitude of a relative peak in the HVPSR still might be very small (perhaps less than unity!), because the "amplification" effect of site resonance is acting on much smaller horizontal motions.

Another possibility that we cannot rule out, however, is that the model underlying equation 1 is incorrect, that the observed HVPSR peaks are produced by a different mechanism than multiply reflected SH waves. It is plausible, indeed likely, that much culturally generated surface ground motions propagate from sources of vertical motion as Rayleigh waves (e.g., Stephenson, 2002; Asten, 2003). The ellipticity of particle motion expected in Rayleigh waves would be frequency-dependent and, near a strong resonance peak produced by appropriate shallow structures, dominated by horizontal motion. The frequencies over which horizontal motion dominates would be close to those expected from Equation 1, however, motions would be much more complex and, because Rayleigh waves are a combination of P and SV waves, be dependent on the P-wave structure as well. Another possible explanation why our noisy sites with nearby noise sources did not produce as clean resonance peaks as those with more distant noise sources might be if fundamental mode surface waves (being an interference phenomenon) take some distance to form, they may not be observable, or may have different characteristics adjacent to the source. This would imply that our Vs estimates are systematically biased. We will reserve a more thorough analysis of this more for future work perhaps using data from seismic arrays.

We believe that our observations reflect systematic changes in the shallow geologic structure of the Mississippi embayment, however we are unsure about their exact interpretation. We feel that this uncertainty does not negate the importance of these observations. We are not aware of other studies that have observed different resonance of different structural levels at the same site in spectral ratios. And, in comparison with other geophysical techniques, the HVPSR technique appears to have performed in a comparable manner as far as characterizing the regional variations of a shallow geological feature (the Memphis Loess).

Table 1. Post-Midway geologic units underlying the Memphis area. (Modified from Graham and Parks, 1986).

System	Series	Stratigraphic Unit	Thickness (m)	Lithology
Quaternary	Holocene & Pleistocene	Alluvium	0-53	Sand, gravel, silt, and clay. Underlies the Mississippi alluvial plain and alluvial plains of streams in the Gulf Coastal Plain. Thickest beneath the Alluvial Plain where commonly between 30 and 45 m thick; generally less than 15 m thick elsewhere.
	Pleistocene	Loess	0-20	Silt, silty clay, and minor sand. Principal unit at the surface in upland areas of the Gulf Coastal Plain. Thickest on the bluffs that border the Mississippi Alluvial Plain; thins eastward from the bluffs.
Quaternary & Tertiary(?)	Pleistocene & Pliocene	Fluvial deposits	0-30	Sand, gravel, minor clay and ferruginous sandstone. Generally underlie the loess in upland area, but are locally absent. Thickness varies greatly because of erosional surfaces at top and base.
Tertiary	Eocene	Jackson Formation and upper part of Claiborne Group, includes Cockfield and Cook Mountain Formations	0-110	Clay, silt, sand, and lignite. Because of similarities in lithology, the Jackson Formation and upper part of the Claiborne Group cannot be reliably subdivided based on available information. Most preserved sequence is the Cockfield and Cook Mountain Formations undivided, but locally the Cockfield may be overlain by the Jackson Formation
Tertiary	Eocene	Memphis Sand	152-271	Sand, clay, and minor lignite. Thick body of sand with lenses of clay at various stratigraphic horizons and minor lignite. Thickest in the southwestern part of the Memphis area; thinnest in the northeastern part.

Figure Captions

Figure 1. Geologic Setting and Sampling Locations Within the Memphis Metropolitan Area.

a) Location map for the Mississippi embayment (ME in inset). Contours of unconsolidated sediment thickness are taken from Bodin and Horton, 1999. Dark dashed line is boundary of ME from Stearns, 1957. Light dashed box is the study area.

b) Generalized shallow geological cross section across MMA. See Table 1 for geologic descriptions of soils.

c) Map of generalized surface geology in southwestern Tennessee and bordering eastern Arkansas. Open triangles are sampling locations for the results shown in Figure 4. Additional highest-quality ground motion measurements with nearby borehole control of loess thickness, as discussed in text, are shown as solid black dots (and used in the analysis shown in Figure 5). Sites with letters within circles are the the four sites examined in greater detail (see also Figure 6). OP = Overton Park, SJ = Saint Judes Hospital, SF = Shelby Forest, and TV = TVAC.

Figure 2. Typical Broad Band HVPSR from MMA. T_o is the peak correlated with the fundamental resonance of the whole unconsolidated sediment column, T_1 with the second mode and T_L with the low-velocity surface sediments.

Figure 3. Example of 5Hz Peak and Uncertainty Assignment. T_L is the reported period of the peak, and $\pm\varepsilon$ represent the picking uncertainty as discussed in the text.

Figure 4. Correlation of T_L with Shallow Geology in the MMA. HVPSR values from an approximate transect perpendicular to the strike of geologic contacts in the ME, sites shown as triangles in Figure 1c. Segment A sites are on the active Mississippi River alluvial floodplain. Surface geology of Segment B sites is loess, the thickness of loess for Segment B sites is shown by solid black squares, and scaled on right side of figure. Surface geology of Segment C sites are upper Eocene formations (Figure 1c).

Figure 5. Regression of T_L period with Loess Thickness Within the MMA. The best-fit line (in a least-squares sense) passing through the origin is shown as a solid line. Dashed lines are 95% confidence intervals on the slope of the best fitting line. Error bars for the period of the HVPSR peaks were defined by the uncertainty in picking the peak as described in the methods section, while an error of ±1 m was assigned to the loess thickness (Smith, 2000).

Figure 6. HVPSR From Four Sites (see Figure 1 for locations). A) Overton Park, observed T_L peak periods shown as black arrows, values expected as discussed in text shown as grey arrows. B) Shelby Forest; as for 6a, but range of expected values indicated by grey bar. C) Saint Judes Hospital; 12 hour-long HVPSRs are shown. D) TVAC; two one-hour long HVPSRs are shown.

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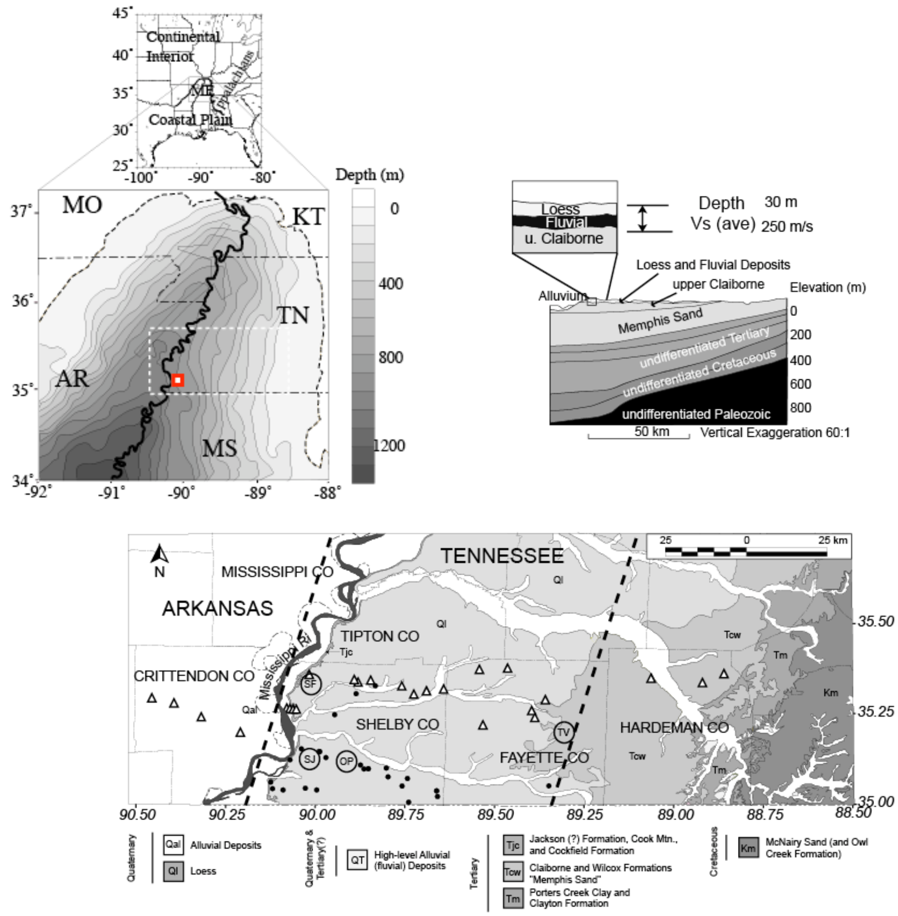

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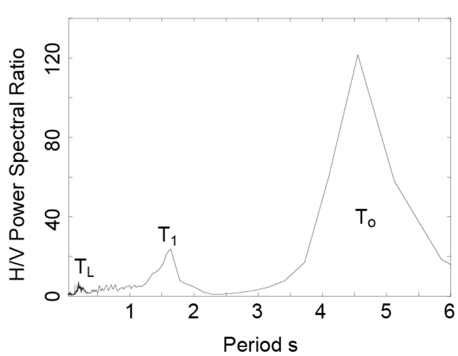

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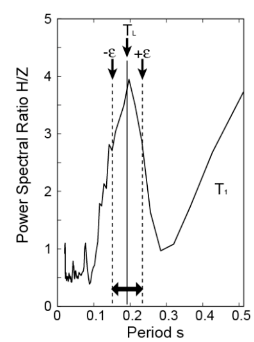

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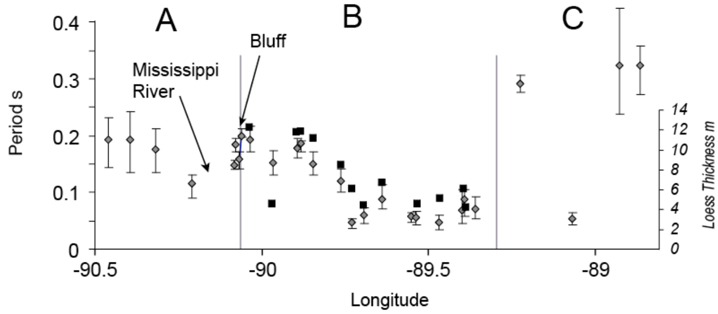

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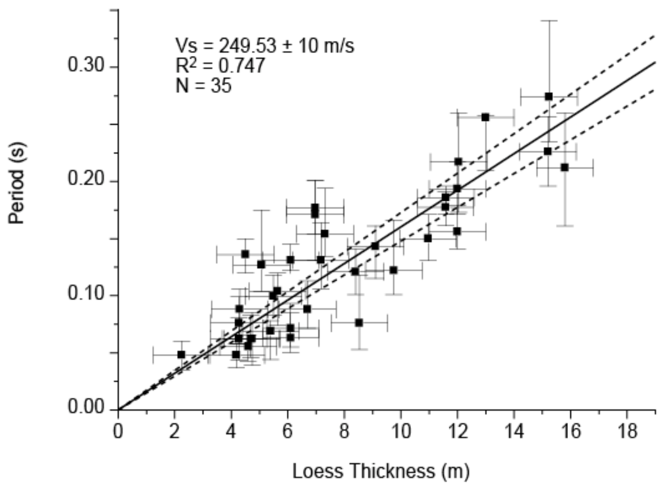

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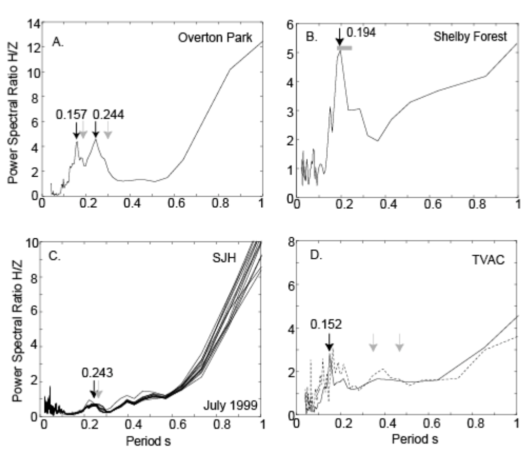

Figure 6.

Contact Information and Data Availability

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Educational Impact of Project

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Bibliography of Publications Resulting from Project

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